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EP 0719002 A1 US 4835483 A

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(54) **AFC in a DMT receiver**

(57) In a Discrete Multi Tone or Orthogonal Frequency Division modulation transmission system using Quadrature Amplitude Modulation within the individual tones of the transmission, specific quadrature data values within a single tone or multiple tones are used as a synchronisation tone or tones, the value of the quadrature portion of the demodulated signal at the receiver is compared (4) with a preset value at the receiver which corresponds to the quadrature value imposed on the signal at the transmitter and any difference between these two compared values is used to indicate a value by which the receiver local oscillator is out of synchronisation with the transmitter oscillator and this value is used within a phase locked loop which includes the receiver local oscillator 8 and the demodulation process 10, to correct the frequency of the receiver local oscillator.

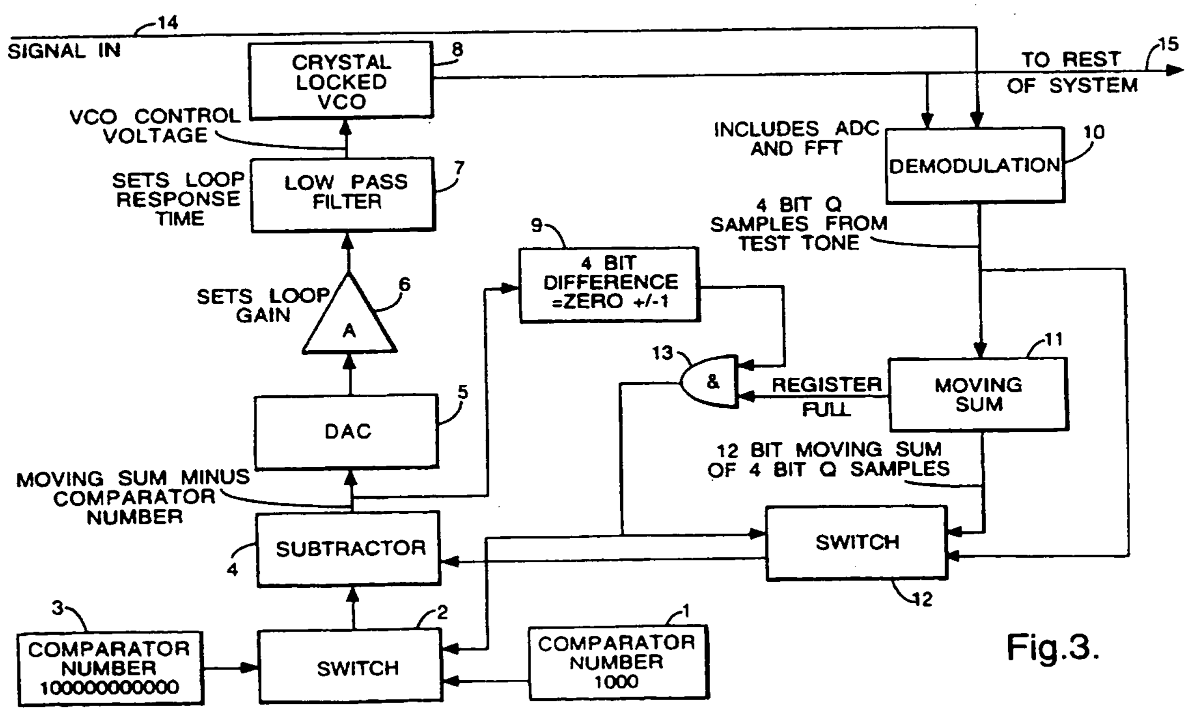

Fig.3.

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig.1.

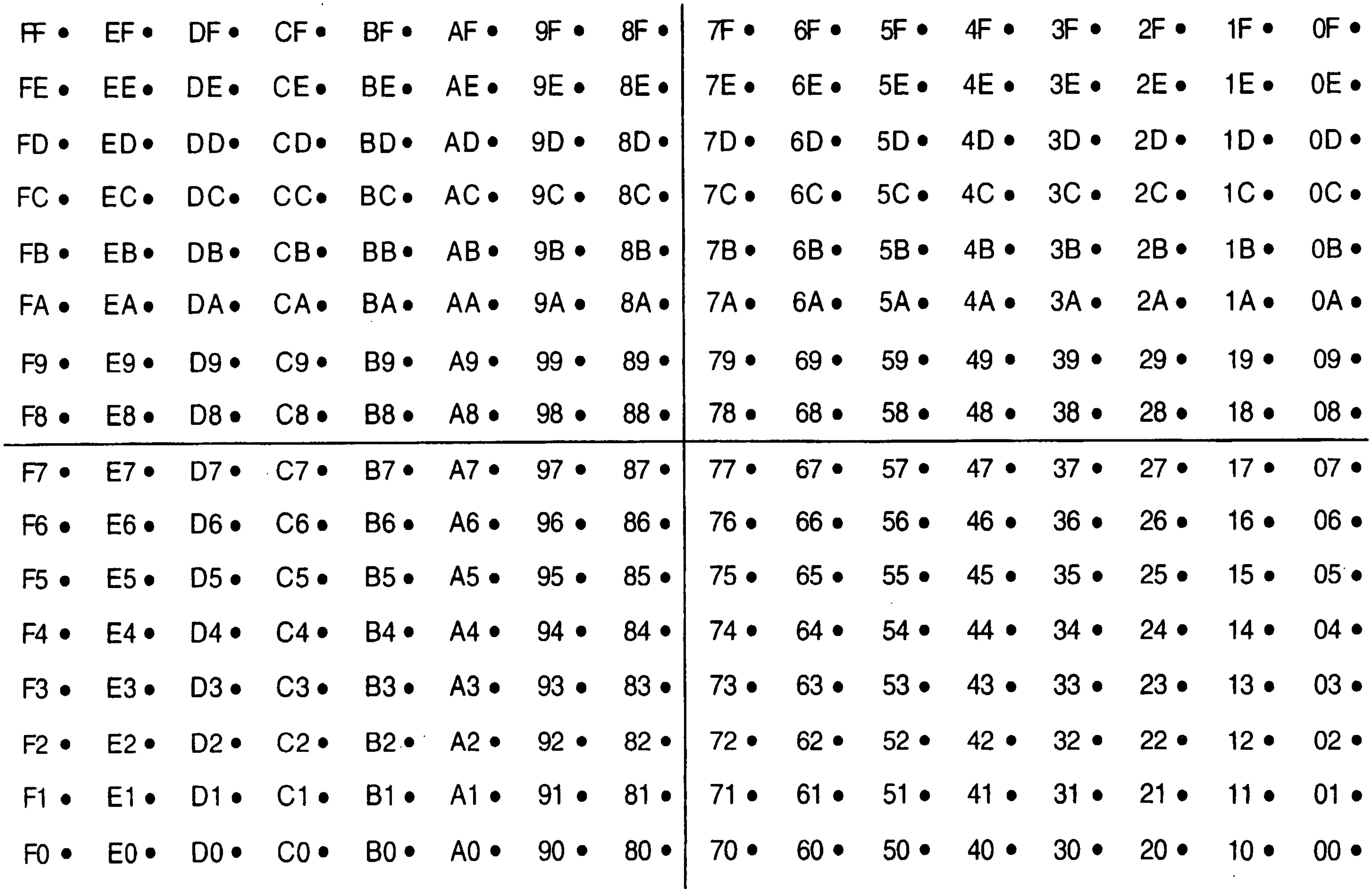
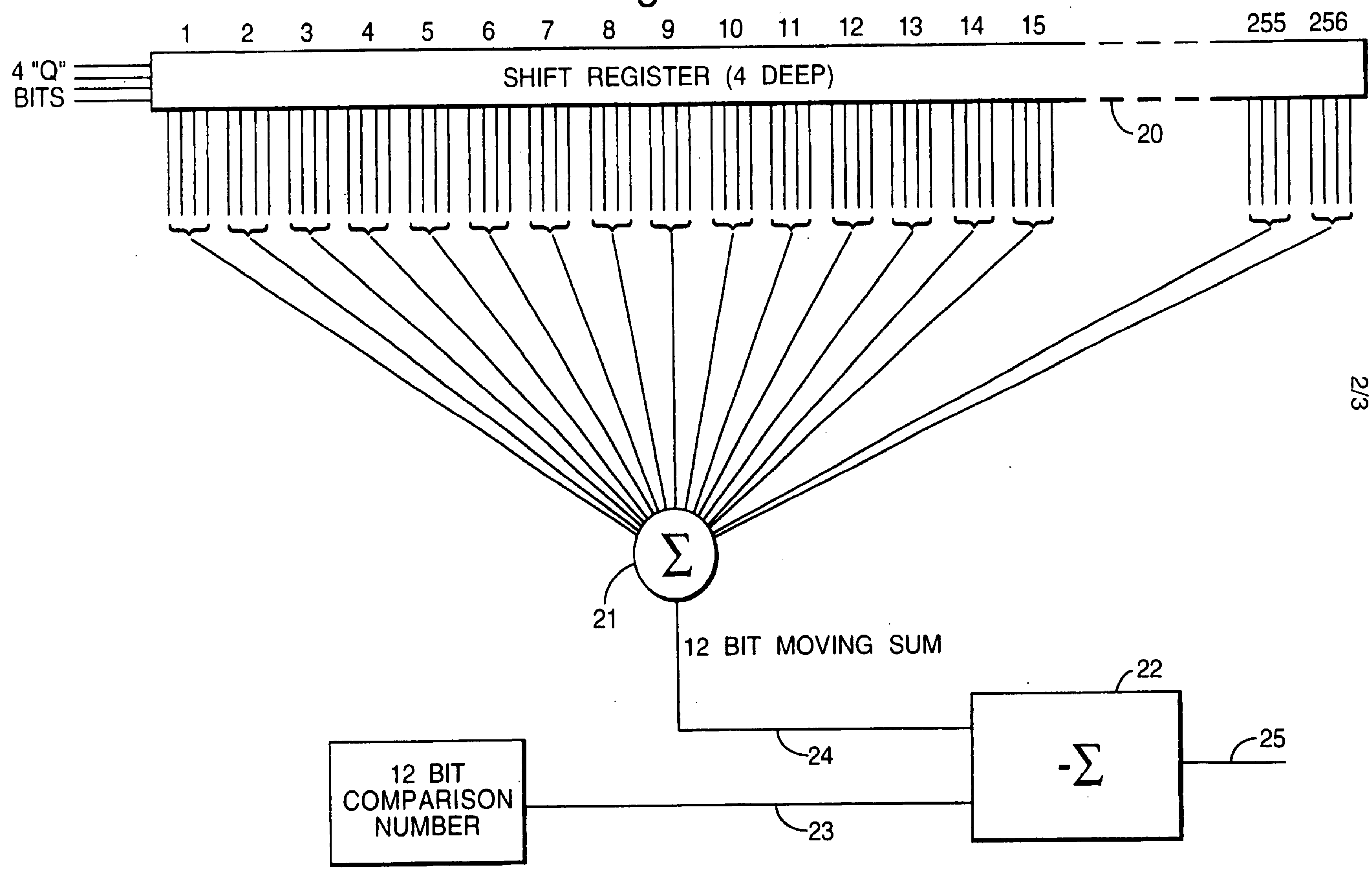

FF EF DF CF BF AF 9F 8F 7F 6F 5F 4F 3F 2F 1F 0F
FE EE DE CE BE AE 9E 8E 7E 6E 5E 4E 3E 2E 1E 0E
FD ED DD CD BD AD 9D 8D 7D 6D 5D 4D 3D 2D 1D 0D
FC EC DC CC BC AC 9C 8C 7C 6C 5C 4C 3C 2C 1C 0C
FB EB DB CB BB AB 9B 8B 7B 6B 5B 4B 3B 2B 1B 0B
FA EA DA CA BA AA 9A 8A 7A 6A 5A 4A 3A 2A 1A 0A
F9 E9 D9 C9 B9 A9 99 89 79 69 59 49 39 29 19 09
F8 E8 D8 C8 B8 A8 98 88 78 68 58 48 38 28 18 08
F7 E7 D7 C7 B7 A7 97 87 77 67 57 47 37 27 17 07
F6 E6 D6 C6 B6 A6 96 86 76 66 56 46 36 26 16 06
F5 E5 D5 C5 B5 A5 95 85 75 65 55 45 35 25 15 05
F4 E4 D4 C4 B4 A4 94 84 74 64 54 44 34 24 14 04
F3 E3 D3 C3 B3 A3 93 83 73 63 53 43 33 23 13 03
F2 E2 D2 C2 B2 A2 92 82 72 62 52 42 32 22 12 02
F1 E1 D1 C1 B1 A1 91 81 71 61 51 41 31 21 11 01
F0 E0 D0 C0 B0 A0 90 80 70 60 50 40 30 20 10 00

Fig.2.


4 "Q" BITS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
255
256
SHIFT REGISTER (4 DEEP)
20
21
12 BIT MOVING SUM
22
-Σ
25
24
23
12 BIT COMPARISON NUMBER

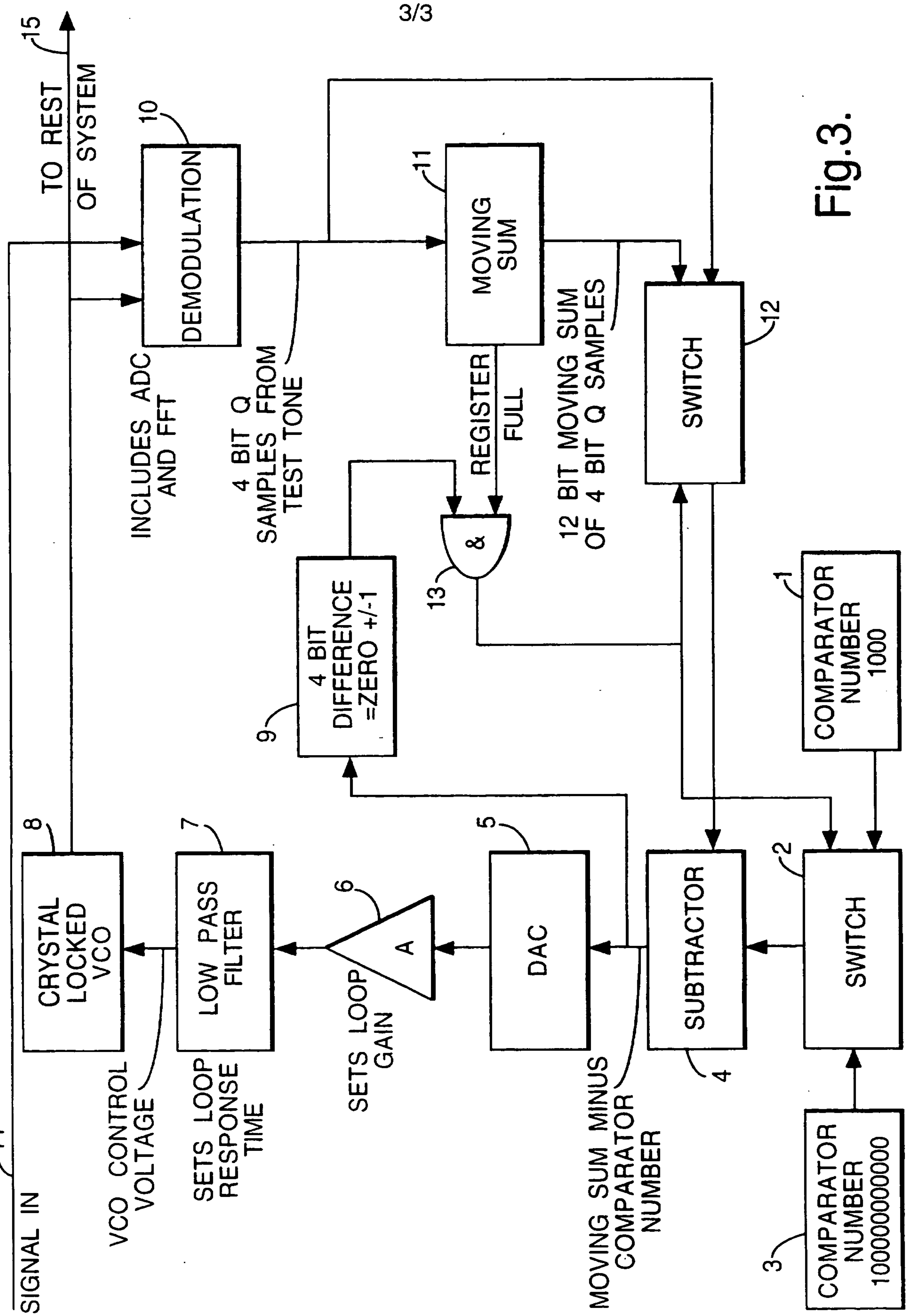

TO REST OF SYSTEM
15
10
DEMODULATION
INCLUDES ADC AND FFT
4 BIT Q SAMPLES FROM TEST TONE
11
MOVING SUM
REGISTER FULL
12 BIT MOVING SUM OF 4 BIT Q SAMPLES
SWITCH
12
&
13
4 BIT DIFFERENCE =ZERO +/-1
9
COMPARATOR NUMBER 1000
1
SIGNAL IN
14
CRYSTAL LOCKED VCO
8
VCO CONTROL VOLTAGE
LOW PASS FILTER
7
SETS LOOP RESPONSE TIME
A
6
SETS LOOP GAIN
DAC
5
MOVING SUM MINUS COMPARATOR NUMBER
SUBTRACTOR
4
SWITCH
2
COMPARATOR NUMBER 100000000000
3

Fig.3.

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AFC IN A DMT RECEIVER

A Discrete Multi Tone (DMT) system transmits a series of Quadrature Amplitude Modulation (QAM) modulated, band limited, series contiguous tones. These tones are therefore modulated in both amplitude and phase. This signal is generated from the original bit stream by a process of breaking down that bitstream into a series of lower bit rate parallel bit streams, separating these individual bit streams into I and Q sub bit streams, and applying those bit streams to a multi point Inverse Fast Fourier Transform process. The result of this process is then applied to a Digital to Analogue Converter (DAC) the output of which will be the tone series as described above.

The received signal, which is applied to an Analogue Digital Converter (ADC) should consist of the above signal. After A to D conversion and processing by a Fast Fourier Transform (FFT), the bit streams should be the same as those applied to the Inverse Fast Fourier process and will consist of multiple data "nibbles", each of half the length of the data byte of which they are part. Each of these bytes will correspond to one tone in the DMT tone series, and the nibbles will correspond to the I and Q components of that QAM modulated signal, the I components being amplitude modulated and the Q components being phase modulated.

For example, if the transmitted signal was 256 QAM modulated, then the received signal will consist of 8 bits, 4 in the Q dimension and 4 in the I dimension. The I and Q positions in the two dimensional QAM constellation, which correspond to the value of

the transmitted byte, are arbitrary; that is, any position can be assigned to any byte value.

According to the present invention there is provided a method for use with a Discrete Multi Tone or Orthogonal Frequency Division modulation transmission system using Quadrature Amplitude Modulation within the individual tones of the transmission, wherein specific quadrature data values within a single tone or multiple tones are used as a synchronisation tone or tones, the value of the quadrature portion of the demodulated signal at the receiver is compared with a preset value at the receiver which corresponds to the quadrature value imposed on the signal at the transmitter and any difference between these two compared values is used to indicate the amount by which the receiver local oscillator is out of synchronisation with the transmitter oscillator and this value is used within a phase locked loop which includes the receiver local oscillator and the demodulation process, to correct the frequency of the receiver local oscillator.

The present invention will now be described by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates a QAM constellation for use in the present invention;

Figure 2 illustrates a moving sum generator and comparator; and

Figure 3 illustrates apparatus for use in locking the local oscillator to an incoming DMT signal.

In the present invention a constellation is used in which the byte values increase at a uniform 1 bit rate in both the I and in the Q dimension. This arrangement is illustrated in Figure 1. This uses a 256 QAM constellation as an example, although, obviously, the same incremental byte positioning scheme can be equally applied to other QAM modulation levels. 256 QAM is also used here since it is possible to use hexadecimal notation to describe the byte values, simplifying the diagram considerably.

As can be seen, the I values, in this particular example, are assigned to the four least significant bits, this nibble being assigned a hexadecimal number from 0 to F, incrementally vertically, while the Q values are assigned to the four most significant bits, incrementing horizontally. It can be seen that the value of any byte specifies its position in the constellation exactly.

It will be noticed that the diagram is divided into four quadrants, as is a standard QAM constellation diagram. However, in this case, the quadrant lines do not represent the dividing lines between groups of numbers with the quadrant indicated by the two most significant bits. Rather, the horizontal line represents an amplitude of 50% of the available maximum amplitude in the I dimension, while the vertical line represents a 0° phase shift in the Q dimension, with positions to the left of the line representing a negative phase shift in the signal and positions to the right representing a positive phase shift. Assuming a maximum phase shift of + and - II/2 then each increment or decrement in

the Q dimension represents a phase change of 12°.

If a particular tone is assigned the permanent value of 88H (10001000) then that tone will appear as a sine wave with an amplitude of 56.25% of the maximum available amplitude and a phase shift one position negative with regard to zero phase shift. This tone then becomes a pilot tone from which information regarding the phase/frequency of the tone at the receiver can be extracted.

Considering the manner in which this system is used to control the frequency and phase of the local oscillator.

It is assumed that the local oscillators in both transmitter and receiver are crystal types. Under these circumstances, the amount of frequency variation between transmit and receive is extremely unlikely to exceed half the bandwidth of one tone. However, even relatively minor frequency deviations within this limit can severely disrupt the demodulation of an incoming DMT signal. Such deviations may be caused by variations in temperature between transmitter and receiver or by crystal aging. The simplest way to envisage the affect of this deviation is to imagine the affect on a single value repeated in each sample. This will appear as a sine wave demodulation. In the receiver the affect is to create a demodulated value which will vary at a frequency which is the beat frequency between the incoming sine wave and the difference between the transmit and receive clock. Clearly, the correlation between this varying level and the transmitted level will be very low and the received signal will be almost entirely errored.

To ensure accurate demodulation of the received signal, the receive clock must be in both frequency and phase lock with the transmitter.

It might be thought that it would be simple to send a synchronising tone to which the receiver might lock. However, a consideration of the nature of a DMT signal will lead to an understanding of why this is not as viable alternative. A DMT signal comprises multiple series contiguous tones. Any tone sent within this overall DMT signal will need to be very pure to prevent harmonics from interfering with neighbouring DMT tones. Additionally, the analogue filters in the receiver will need to be extremely accurate to exclude the neighbouring DMT tones, which are both phase and amplitude modulated, from interfering with the pilot tone. In a typical DMT system, the data carrying tones might have a bandwidth of 16 KHz. These may be modulated to 10 bits per Hz, or more. This means that, if the test tone is not to be perceived as noise by neighbouring tones, it must attenuate the signal by at least 66 dB within 8 KHz of the test tone frequency. It is expected that a broadband application of DMT will require the signal to extend to several megahertz, but if we accept a test tone signal of 1 MHz as being typical of the frequency range involved, then the receive test tone filter will need a Q value of over 1000. Further, the output of the filter must be free from ringing and any other amplitude variations. It is not reasonable to expect such a filter to be produced at a price which will make a DMT system viable.

Any test tone send outside the DMT frequency envelope will be subjected to phase delays and attenuations differing from the DMT signal and as such will not be suitable as a locking signal. At frequencies below the DMT envelope, the phase environment worsens while at frequencies above it the attenuation becomes excessive. Further, in a multi-pair cable, where the vast majority of DMT signals exist, such a tone may be subject to cross talk from other strong signals in the cable, such as Integrated Services

Digital Network (ISDN) or High-Speed Digital Subscriber Lines (HDSL).

The answer to this problem is to include the synchronising signal within the DMT signal, as described above.

Before the receiver can be phase locked to the incoming signal, it must first be frequency locked. That is, while the receiver local oscillator may not be exactly in phase with the incoming signal, it will be at the correct frequency. This is achieved by the operation of the first series of events within the operation of the present invention. Accurate phase lock will be achieved by the second and on-going series of events performed by the present invention.

The transmitted synchronisation signal will be received and demodulated by the FFT block in the receiver to a number which will be indicative of the original transmitted number, the effects of phase noise, and the amount of phase and frequency variation of the receive local oscillator from the transmit local oscillator.

While this signal may have been transmitted as 1000, it may be received as 1001 or 0111 in the event of a relatively small deviation, or, in the worst controllable cases, as 1111 or 0000. However, in this first reading, it can be seen that the amount and rate of deviation from the desired phase and frequency is an indication of how much the local oscillator frequency must be pulled in order to achieve frequency synchronisation with the incoming signal.

Reference to Figure 3 will assist in understanding the following explanation.

In this first stage of the operation of the system, the demodulated four bit Q number will be compared with a four bit number 1 set to 1000B. Switch 2 is, at this initial point, set to connect Comparator Number 0001 to the Subcontractor 4. Switch 12 is set to connect the demodulated 4 bit Q samples from the test tone from the demodulator 10 directly to the Subtractor 4. The Digital Analogue Converter (DAC) 5 will receive a signal from the Subtractor which is the difference between the output of the modulator and the Comparator number. This will be a three bit plus sign digital number which will be applied to the four most significant bits of the DAC. The output of the DAC, which will be a 16 level analogue signal is applied to the loop gain amplifier 6 which sets the gain of the loop. The output of the loop gain amplifier is passed to the Low Pass Filter 7 which sets the loop response time. This response time is dependent on the expected probable maximum deviations between the transmit and receive oscillator frequencies. Normal phase lock loop considerations should be applied here.

The Voltage Controlled Oscillator (VCO) Control Voltage is now applied to the Crystal Locked VCO 8. While this is a crystal oscillator, it must be designed so that an applied voltage may be used to alter the frequency of operation within defined limits. This is a standard crystal oscillator implementation and will not be described in detail here. The effect of the control voltage on the oscillator will be, as in a standard phase locked loop, to attempt to reduce the control voltage to zero. Since this only occurs when the local oscillator is operating at the same frequency as the distant transmit oscillator, that is, when the transmitted number 1000B is accurately demodulated from the incoming

signal, this will have the affect of locking the local oscillator to the frequency of the transmit oscillator.

The accuracy of this simple system, however is limited to the number of points that the Q bits of the QAM constellation provide. In the case of the example here, 256 QAM, this is 16 points. A system whose phase accuracy is limited to 1 in 16 will not be sufficiently accurate to ensure that the received signal is always correctly demodulated, since this degree of accuracy is not sufficient to ensure that the local oscillator is pulled exactly to the required phase. The oscillator may be at a phase which places the actual received signal point near but not on the required point, leaving the overall signal more vulnerable to phase noise received with the signal.

In order to improve the accuracy of the signal, a moving sum of the digital value of the Q component of the pilot tone is used to generate a 12 bit digital number which is compared against another 12 bit number to determine whether the local oscillator is at the correct phase and by how much its phase differs from the desired phase.

The four "Q" bits from each received sample are input to a four wide 256 long shift register 20. The parallel outputs of this shift register 20 are summed to a 12 bit number 24 in Summer 21. Samples reaching the end of the shift register are discarded. This leads to a sum which will change as the value of the input Q nibble changes. However, since 256 samples are summed and compared simultaneously, this has the effect of averaging 256 samples and comparing them to a set comparison number 23 at an accuracy of one part in 4096.

The comparison number 23 is set to 2048 (800H), which is both the sum of 256 Q samples of 1000B and half the highest number available (FFFH). If all the samples within the 256 samples are demodulated to 1000 (8H) this will be the sum of all the samples in the shift register. If the output from Summer 21 and the 12 bit comparison number 23 are equal then the sum 25 from Summer 22, which is in fact a Subtractor, will be zero.

If any of the samples within the shift register 20 have been perturbed by noise in the transmission medium and demodulated to figure which is higher or lower than 8H, then the 12 bit moving sum 24 will be higher or lower than 800H. When compared with the 800H 12 bit comparison number 23, this will generate an output from Summer 2 which is an indication of the average amount, sampled over 256 samples, by which the samples are deviating from the required demodulation number.

While noise may perturb the phase of the received QAM signal on a sample by sample basis, this noise will tend to average out over the sampling period. Should the local oscillator be out of phase synchronisation with the incoming signal, however, the phase of the received QAM signal will not conform exactly, or at all, with the required signal.

If, for example, the received signal is lagging by 6°, then the Q bits are equally likely to demodulate to either 1000 or 1001, that is 8 or 9 in hexadecimal format. Assuming an equal statistical likelihood of the demodulator producing either of these figures with a received phase at 6°, then the moving sum will become 880H. The difference between this and 800H is 80H, or 128D. This figure represents the deviation of the receiver local

oscillator from synchronisation with the incoming signal.

This method of generating a digital number representing the deviation of the local oscillator from its required frequency is made part of the phase locked loop, as shown in Figure 3.

Before the system can move into this more accurate phase of its operation, two conditions must be fulfilled:

1. the output of the Subtractor 4 must be within one bit from zero for the initial frequency lock circuit operation, and

2. the moving sum register 11 must be full.

An absolute magnitude Comparator 9, labelled "Bit Difference = zero +/- 1" in Figure 3, will detect when the output of the Subtractor has achieved zero + or - 1 bit. The Moving Sum Generator 11 will also produce an output when it is full. These two conditions are detected by the And Gate 13 the output of which is used to set switches 2 and 12 to positions required for the next, more accurate, phase of operation to commence.

It will be noticed that the Moving Sum Generator 11, as shown in Figure 2, requires 256 samples to fill. While this is occurring, the loop will have stabilised sufficiently for output of the Subtractor to have decreased to zero, plus or minus one bit. The reason for

the acceptance of outputs which are not exactly zero is that allowance must be made for noise in the received signal, which may perturb the Subtractor output by one bit.

It will be noticed that the output of the Demodulator 10 is also connected to the Moving Sum Generator 11. Under the influence of And Gate 13, the input to the Subtractor 4 will be switched 12 from a direct input from the modulator to the output of the Moving Sum Generator 11. This will be a 12 bit number. At the same time, switch 2 will connect the 12 bit Comparator 3 to the other input of the Subtractor 4.

It should be noted that the four bit number used during the initial, frequency locking, phase of operation, corresponds to the four most significant bits of the 12 bit number.

The Moving Sum Generator 11 will operate as described above, producing a 12 bit number for comparison with the preset Comparator number 10000000000B. The output of the Subtractor 4 will now be an 11 bit plus digital signal.

It will be remembered that, while the local oscillator will be locked to the correct frequency, it will probably not be set to the correct phase to ensure accurate demodulation of the incoming signal. The effect of the second phase of operation, that is with the Moving Sum Generator in operation, is to increase the accuracy of the loop to a factor of 1 in 4096. This is more than sufficient to ensure accurate demodulation of the incoming signal.

It will be remembered that, while the local oscillator will be locked to the correct

frequency, it will probably not be set to the correct phase to ensure accurate demodulation of the incoming signal. The effect of the second phase of operation, that is, with the Moving Sum Generator in operation, is to increase the accuracy of the loop to a factor of 1 in 4096. This is more than sufficient to ensure accurate demodulation of the incoming signal.

An examination of the foregoing system will show that it relies on noise to perturb the incoming signal from the position it would have occupied had it relied on the variation in phase between the incoming signal and the local oscillator alone. In the absence of noise, an incoming signal which was, for example, only 5° from the required phase, would always demodulate to the transmitted signal. Under these circumstances, the local oscillator will remain 5° out of phase with the incoming signal. In fact, the local oscillator can wander up to 6° from its required phase before it starts to affect the incoming signal demodulation.

This may be sufficient for a channel in which there is little or no noise, however, if the test tone channel is relatively noise free, and other channels within the DMT raster have noise imposed upon them, then errors will occur within the noisy channels. It is essential, therefore that the system pull the local oscillator as close as possible to the required phase.

To overcome this problem, once the And Gate 13, produces an output, this condition is transmitted to the transmitter via the DMT control channel and a noise signal is imposed on the test tone at the transmitter. This noise will be of a sufficient amplitude to produce

a normal distribution at the receiver, with one standard deviation corresponding to 6° of phase shift. In order to prevent the occasional deviation beyond Π/2, the applied noise is amplitude limited to prevent such deviations.

This noise will have the effect of causing the four bit inputs to the Moving Sum Generator 11 to vary in a chaotic, but statistically predictable manner, producing a moving sum which will more accurately reflect the variation in phase between the transmit and receive local oscillators.

If, for example, the phase of the local oscillator is such that it is placing the 0001 constellation point 5° from its required position, the imposed noise will tend to push the deviated point to positions where it will be demodulated to adjacent numbers. These adjacent numbers will be added to the moving sum and will change its overall value. The number of times which the deviated point is pushed to adjacent numbers will depend on the strength of the noise signal and the amount of deviation from the desired constellation point. The overall affect of this is to alter the moving sum to give an accurate indication of the amount of local oscillator deviation from the desired phase and, via the operation of the phase locked loop, to pull the local oscillator to the desired phase for most accurate demodulation.

As a further development of this principle, the noise environment of the received test tone is measured and fed back to the transmitter. Such noise measurement and feedback is a standard feature of DMT systems. This noise figure is used to set the level of noise imposed on the test tone signal at the transmitter, ensuring that the noise within the

received test tone signal is optimum for increasing the accuracy with which the receive local oscillator is locked to the transmit signal.

CLAIMS

1. A method for use with a Discrete Multi Tone or Orthogonal Frequency Division modulation transmission system using Quadrature Amplitude Modulation within the individual tones of the transmission, using specific quadrature data values within a single tone or multiple tones are used as a synchronisation tone or tones, the value of the quadrature portion of the demodulated signal at the receiver being compared with a preset value at the receiver which corresponds to the quadrature value imposed on the signal at the transmitter and any difference between these two compared values being used to indicate a value by which the receiver local oscillator is out of synchronisation with the transmitter oscillator and this value being used within a phase locked loop which includes the receiver local oscillator and the demodulation process, to correct the frequency of the receiver local oscillator.

2. A method as claimed in Claim 1 wherein the quadrature portions of the signal, demodulated from the synchronisation tone or tones, consisting of a series of partial bytes of half the full byte length, are held for a specified number of demodulation cycle times forming the addenda of a moving sum of these values; which moving sum, whose value varies with the value of the incoming quadrature partial bytes, is compared with a preset number, this number being equal to the value of the moving sum were the inputs to the moving sum to consist of the transmitted values of the quadrature partial bytes, to determine the variation in the values of the incoming quadrature partial bytes averaged over the

sum of the times of the number of demodulation cycles required by the moving sum; which variation is used, within a phase locked loop which includes the receiver local oscillator and the demodulation process, to correct the phase of the receiver local oscillator.

3. A method as claimed in Claim 2 wherein additional noise included within the synchronisation tone or tones, and imposed at the transmitter, is used to perturb the received signal in a chaotic but statistically measurable manner, the phase deviation of this noise being long term statistically zero but short term variable within a truncated normal distribution, which noise perturbs the synchronisation tone or tones such that the tone or tones may be demodulated to values other than the transmitted value, the ratio of such other values within the moving sum providing an indication of the long term variation of the phase of the demodulated synchronisation tone or tones with the required phase of the synchronisation tone or tones.

4. A method of determining the values assigned to the quadrature and in phase elements of a Quadrature Amplitude Modulated signal, these elements increasing or decreasing arithmetically with variations of the phase and amplitude respectively of the transmitted signal, the arithmetic progression allowing the determination of the absolute value of any Quadrature Amplitude Modulated signal from its amplitude and phase.

5. A method as claimed in Claim 1 and substantially as hereinbefore described, with

reference to and as illustrated in the accompanying drawings.

6. In a DMT system using QAM apparatus for locking a local oscillator to an incoming DMT signal substantially as hereinbefore described with reference to and as illustrated in Figures 2 and 3 of the accompanying drawings.

The Patent Office

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Application No:	GB 9622881.2	**Examiner:**	Keith Williams
Claims searched:	1-3,5,6	**Date of search:**	30 January 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H4P (PABC, PAL, PAQ, PSB)

Int Cl (Ed.6): H04L 5/06, 27/38

Other: online WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0719002 A1	Alcatel Bell N V - see columns 3,4	1
A	US 4835483	NEC Corp. - see Fig. 4 (and equivalent EP 0262644)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.